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FIDEX: An Expert System for Satellite Diagnostics

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ABSTRACT

A Fault Isolation and Diagnosis Expert system (FIDEX) was developed for communication satellite diagnostics. It was designed specifically for the recently completed 30/20-gigahertz satellite transponder, developed at NASA Lewis as part of the ACTS (Advanced Communication Technology Satellite) System. The expert system was designed with a generic structure and features that make it applicable to other types of space systems.

FIDEX is a frame-based system that enjoys many of the inherent frame-base features, such as inheritance, message passing, etc. The frame architecture integrates a frame hierarchy that describes the transponder's components, with other hierarchies that provide structural and fault information about the transponder. This architecture provides a flexible diagnostic structure and enhances maintenance of the system.

FIDEX also includes an inexact reasoning technique and a primitive learning ability. Inexact reasoning was an important feature for this system due to the sparse number of sensors available to provide information on the transponder's performance. FIDEX can determine the most likely faulted component under the constraint of limited information. FIDEX learns about the most likely faults in the transponder by keeping a record of past established faults. This permits the system to search first for those faults which are most likely to occur, thus enhancing search efficiency. FIDEX also has the ability to detect anomalies in the sensors that provide information on the transponder's performance. This ability is used to first rule out simple sensor malfunctions.

1. INTRODUCTION

The satellite network of the United States represents a strategic resource for this country. It supports both the commercial and military sectors by providing effective world-wide communications. The reliable operation of each satellite represents a critical goal of NASA.

Satellite reliability is presently maintained through human intervention. When a problem occurs, ground personnel are first made aware of it when the satellite communicates its status to them during a fly-by. They then use telemetry from the satellite to aid them in correcting the fault. This process proceeds through the tasks of: fault isolation, fault diagnosis and fault response. Findings are also recorded for future reference in the event similar conditions reoccur.

Since the mid 80's, NASA has investigated the application of expert system technology to replicate the satellite diagnostic tasks performed by the ground personnel. The principle motivation for this work has been to develop an expert system that can be placed onboard the satellite that will permit the satellite to autonomously perform self diagnosis. Success in this effort offers the potential of improved reliability in situations where ground personnel are not in communication with the satellite quick enough to prevent its failure.

Recently, NASA Lewis completed the development of a 30/20-gigahertz satellite transponder. The transponder is to be integrated with NASA's ACTS (Advanced Communication Technology Satellite) System. The transponder is presently being evaluated within the System Integration, Test, and Evaluation (SITE) system. SITE is a laboratory used by NASA for validating designs and for evaluating and demonstrating satellite communications systems. Figure 1 shows a diagram of the SITE model of the ACTS transponder.

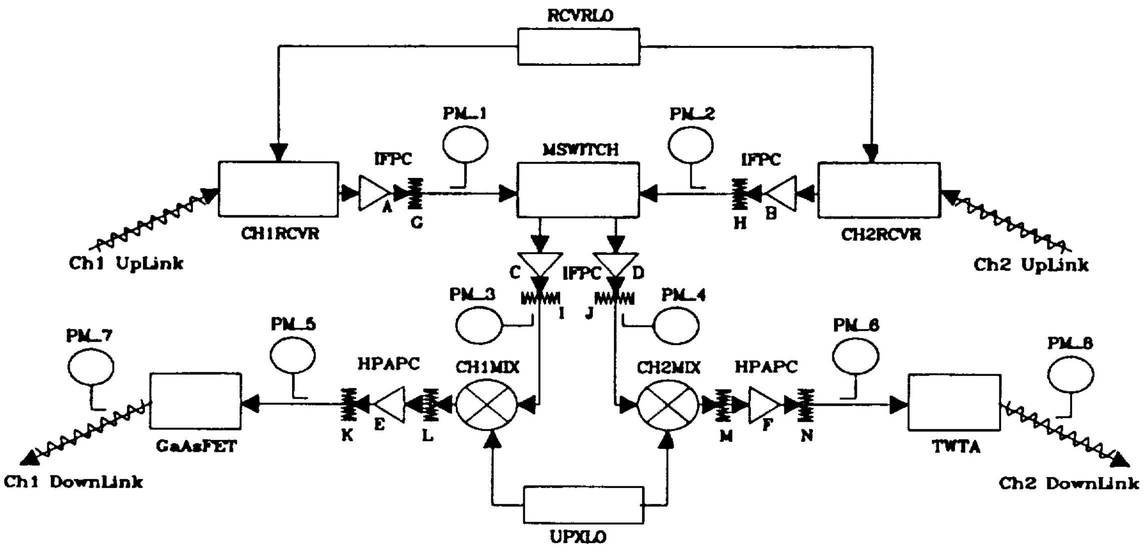


Figure 1. ACTS transponder.

Due to their interest in expert systems, NASA Lewis decided to integrate with the development of the transponder, the design of an expert system which was capable of performing intelligent diagnostics on the new satellite. This ongoing effort has resulted in an expert system called FIDEX.

2. THE PROBLEM

A prerequisite for the design of most expert system projects is the existence of a rich pool of knowledge. In a diagnostic application, this requirement usually dictates that potential fault states of the system under study are well known. Since the satellite used in this study was relatively new, the development of FIDEX had to work under the constraint of limited diagnostic knowledge.

The transponder system is still undergoing evaluation and design changes are possible. These changes could include a modification to component designspecifications or the addition of new components. This evolving state of the design of the transponder required that FIDEX be designed so that it could gracefullyinclude new knowledge as changes are made to the transponder.

Another constraint placed on FIDEX was that it has to work with limited information on the operation of the transponder. The present state of the transponder has only a sparse number of sensors that provide information on the behavior of the system. Available information is limited to power levels and bit-error-rates (BER) at these few select points. The locations of the power sensors are shown in Figure 1 as PM_i.

Faced with these constraints, the work on FIDEX became more of a study effort. Techniques were developed that permitted the system to reason intelligently under the constraint of limited information. In addition, the system needed to easily incorporate changes as modifications were made to the transponder. Finally, FIDEX needed to serve as a guide to NASA for adding additional sensors to the transponder. That is, if we could demonstrate that information presently not available on the transponder's performance could be of value to the expert system, then we could make recommendations for the addition of new sensors that could provide this information. All of these requirements placed a premium on designing a knowledge representation technique and reasoning method that were general and flexible.

3. FIDEX DEVELOPMENT ENVIRONMENT

Since FIDEX needed to be designed in a fashion that would allow it to easily incorporate changes to the transponder, a frame-based approach was taken for knowledge representation. The system was developed on an IBM Model 80 PC using NEXPERT from Neuron Data.

NEXPERT permits an object-oriented style of programming within class/subclass/object hierarchies. It includes message passing through active facets and general rules that can scan the frame hierarchies. It also permits access to database information contained in dBASE III and can execute external C-language programs. In addition, NEXPERT runs in Windows 3.0 and supports dynamic-data-exchange. All of these features of NEXPERT were important in the design of FIDEX as explained in the next several sections.

4. FIDEX ARCHITECTURE

Figure 2 shows a block diagram of FIDEX. The following sections describe each of the blocks illustrated in this figure.

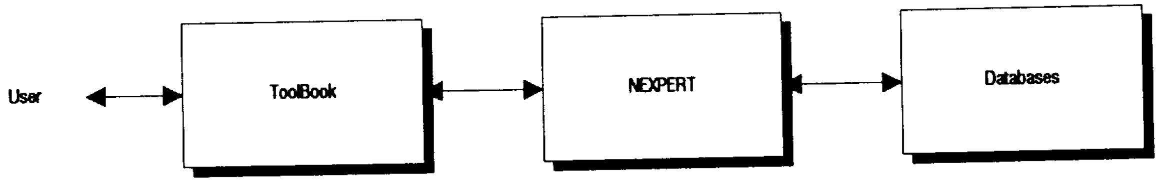


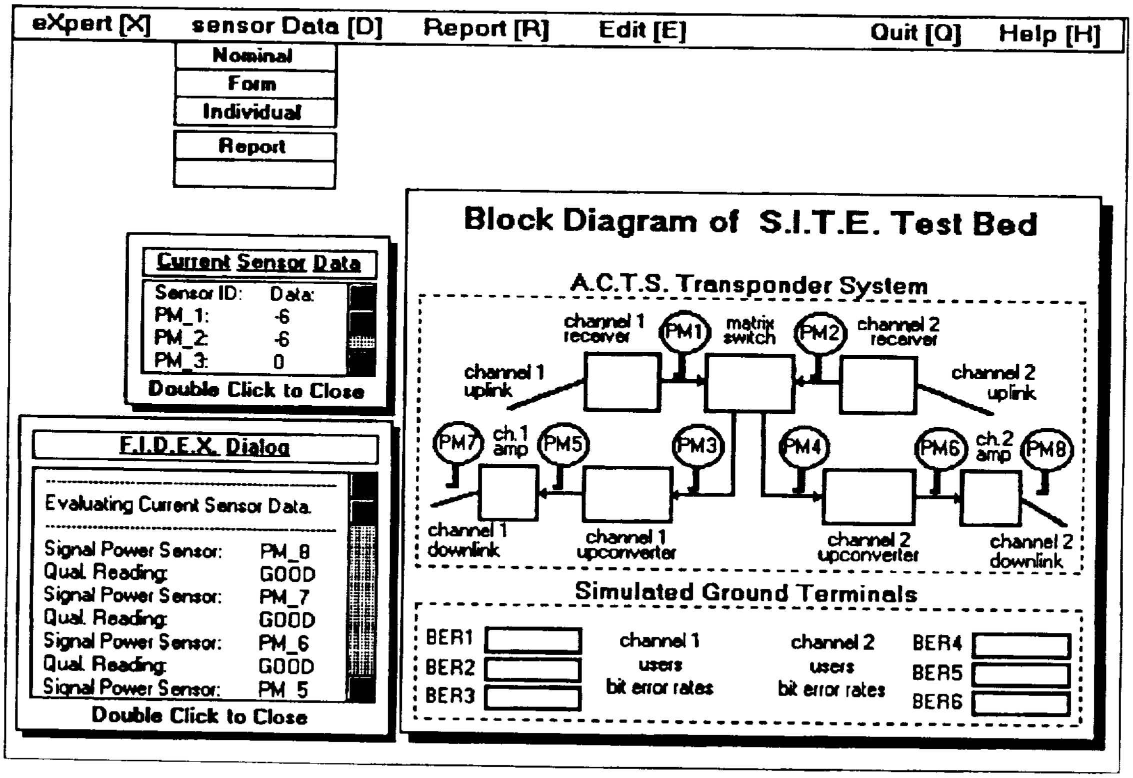
Figure 2. FIDEX block diagram.

4.1 INTERFACE

The long term objective of FIDEX is to permit it to acquire data on the operation of the transponder from a data acquisition system. However, during the development of FIDEX, it was decided to acquire this data interactively from the user through the interface package ToolBook. ToolBook runs in Windows 3.0 and, through dynamic-data-exchange, it can interact with NEXPERT.

The interface is highly menu driven. The user enters information about the condition of the transponder via various forms and prompts. This data is then dynamically transferred to the NEXPERT application where it is evaluated. The interface also allows NEXPERT to prompt the user for information as it is required during the diagnostic process. The results of the evaluation are transferred back to ToolBook where they are reported to the user. These results are conveyed to the user via color changes on interface diagrams and various report forms.

Figure 3 shows an example of the FIDEX interface. The main menu is displayed as the menu bar across the top of the screen. Clicking with the mouse on one of these menu topics displays a pulldown menu for that topic. The pulldown menu for sensor data input is shown that allows several options. First, all the sensors can be initialized to their nominal values by selecting "Nominal" from this menu. The user can also enter sensor data by selecting either "Form" or "Individual." Form input allows the user to input all sensor information via one form. Individual input allows the user to individually alter a sensor value.



Current Sensor Data

Sensor ID:	Data:
PM_1:	-6
PM_2:	-6
PM_3:	0

Double Click to Close

F.I.D.E.X. Dialog

Evaluating Current Sensor Data.

Signal Power Sensor:	PM_8
Qual. Reading:	GOOD
Signal Power Sensor:	PM_7
Qual. Reading:	GOOD
Signal Power Sensor:	PM_6
Qual. Reading:	GOOD
Signal Power Sensor:	PM_5

Double Click to Close

Figure 3. FIDEX interface.

The block diagram of Figure 3 shows the sensors and subsystems of the transponder. This diagram graphically displays the results of FIDEX. For example, if the fault is isolated to a subsystem, FIDEX displays this event by changing the color of this subsystem on the diagram. Also shown on Figure 3 are report forms which display sensor information and the evaluation by FIDEX on the operation of the transponder.

4.2 DATABASE

There are two databases used by FIDEX. One contains information required to initialize the sensors. Each record of this database contains information on the sensor's nominal reading, error tolerances, and other initial parameters. These values are loaded and stored in the appropriate slots of the sensor objects. This method of intialization was chosen to facilitate system maintenance. The second database is used to provide FIDEX a limited learning capability. FIDEX stores the failure history of the transponder system in this database. Each known fault state of the transponder is represented by a record that contains a field which represents the history of that fault state. Following a session with FIDEX, the identified fault has its field value incremented. This recordkeeping is used in future sessions to direct the search towards the most likely faults.

4.3 KNOWLEDGE BASE

FIDEX's knowledge is represented in both frames and rules. Frame hierarchies were developed to represent the transponder's components, subsystems, sensors and faults. These hierarchies were also interconnected in network form to enrich the overall knowledge representation structure. The rules were written to scan the frames and were responsible for fault diagnosis. The following sections describe the frame architecture.

4.3.1 COMPONENTS WORLD

The design of the architecture for the frames used in FIDEX had to first provide a clear and efficient representation of all of the components used in the transponder. This was accomplished using the hierarchical design illustrated in Figure 4, where classes are drawn as circles and objects as triangles. The root node of Figure 4 is a class frame called COMPONENTS that contains properties common to all the children frames shown below it. The children inherit properties, values and methods from the COMPONENTS class. Also, each subclass frame has additional properties that are specific to its name and are inherited by their children. As common to any frame-base system, this structure accommodates the addition of new components as they are added to the design of the transponder.

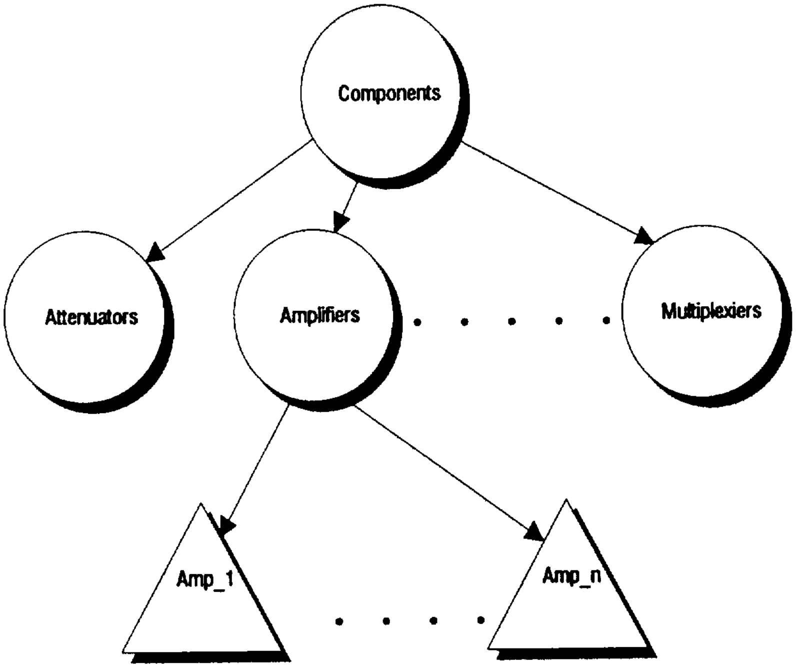


Figure 4. Components frame architecture.

4.3.2 SUBSYSTEMS WORLD

During system diagnosis, one of the first tasks of FIDEX is to isolate the problem to a small set of potentially faulty components. This approach enhances the efficiency of system diagnosis. To accommodate this task, the transponder system of Figure 1 was represented as several interconnected blocks or subsystems. Each subsystem has several different types of components, i.e. amplifier, attenuator, etc. Each of these types of components are represented in FIDEX as previously shown in Figure 4. Therefore, in the representation of the various subsystems, a network was formed that interconnected the world of components with the world of subsystems as illustrated in Figure 5.

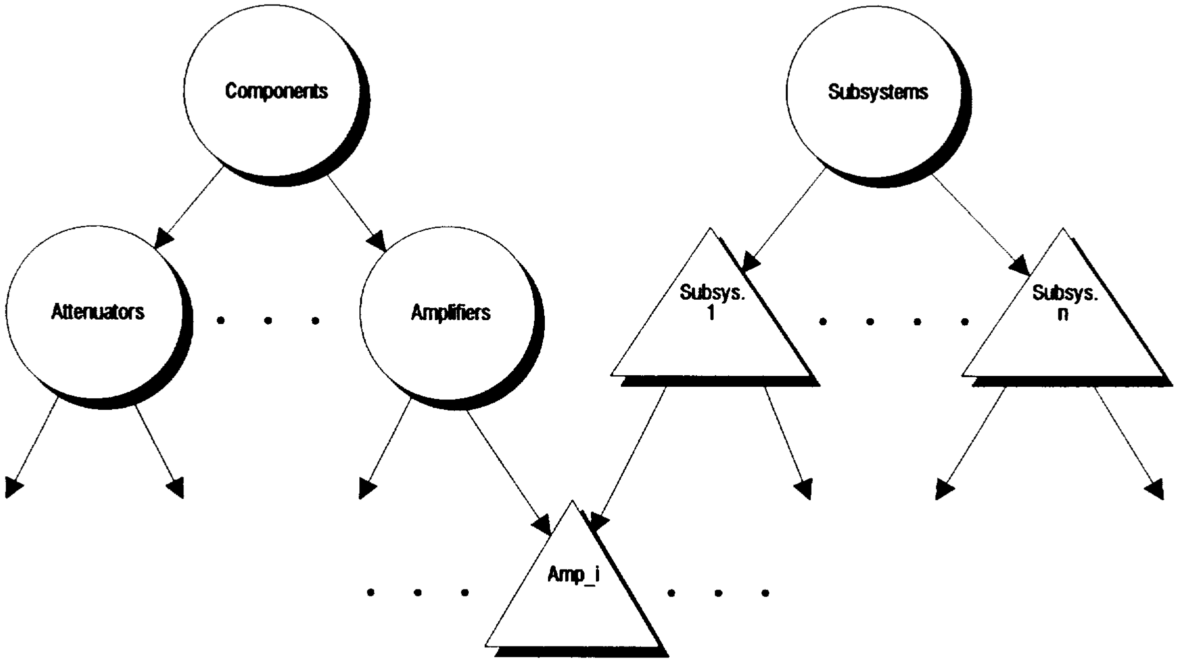


Figure 5. Subsystems frame architecture.

With this architecture, each object frame is associated with two worlds: the components of the transponder and the subsystems of the transponder. The link to the components world can be interpreted as an IS-A link while to the subsystems world as a PART-OF link. This approach not only aids the diagnostic task discussed later, but provides an efficient coding approach where each subsystem component inherits, through multiple inheritance, information from two parents - one provides information on performance while the other on structure.

4.3.3 SENSORS WORLD

Fourteen sensors monitor the operation of the transponder and the relayed signal. Eight of these are power level sensors that report the signal power levels at key locations within the transponder system. The remaining six sensors are BER registers and are located within the ground terminal systems. They report the error, in percentages, incurred when the signal is relayed through the system. Information provided from both the power and BER sensors is used for transponder diagnosis.

FIDEX considers sensors like all other transponder components, a component that could potentially fail. It validates each sensors reading before proceeding to transponder diagnosis. Therefore, each sensor is represented in FIDEX as a member of both the sensors world and the world of components. The frame structure used to represent the sensors in FIDEX is illustrated in Figure 6.

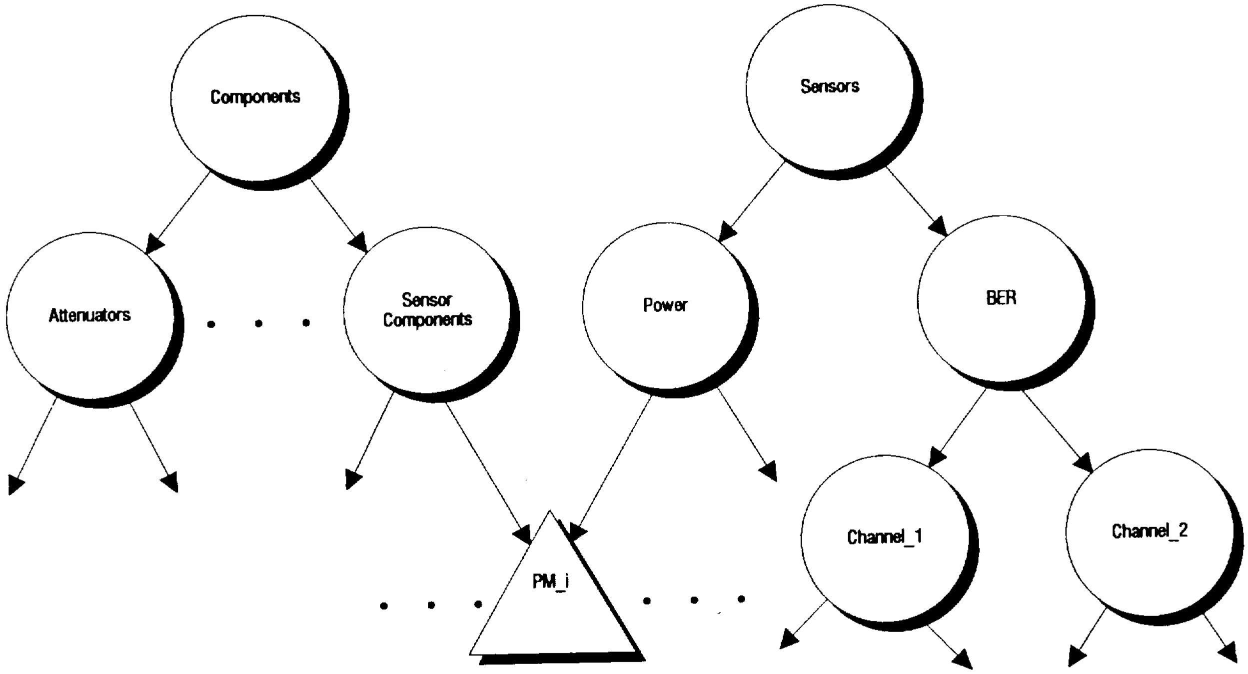


Figure 6. Sensors frame architecture.

4.3.4 FAULT STATES WORLD

The potential transponder fault states were represented in the frame structure shown in Figure 7. Objects to represent each known fault state in the transponder system are attached to nodes under the class of FAULT STATES. These nodes are used to associate the fault state objects with a type of component. For example, fault states which are associated with amplifiers are attached to the AMPLIFIER FAULTS class node.

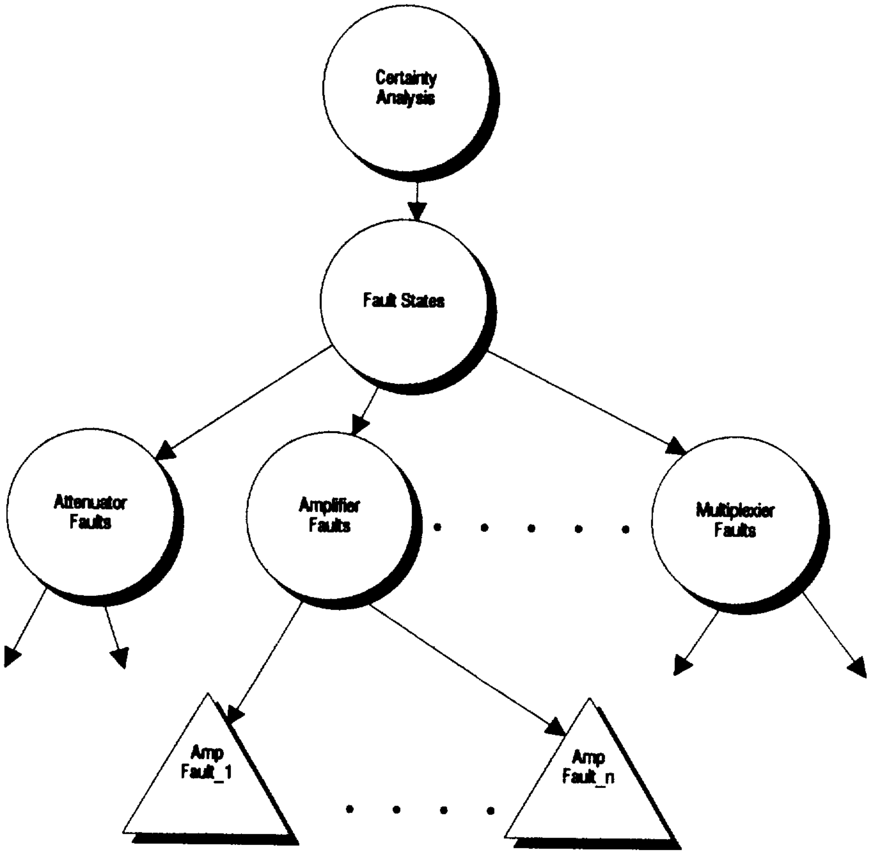


Figure 7. Fault state frame architecture.

The fault state objects of Figure 7 are generic. They can apply to any component that comes from a given class. For example, if FIDEX was considering potential faults of some amplifier, it would consider the same issues regardless of which subsystem it was a component of. This feature offers efficient coding and also permits FIDEX to easily adapt to the addition of new components to the transponder.

5. PROBLEM-SOLVING APPROACH

The problem-solving approach used by FIDEX follows that used by ground personnel who perform satellite diagnostics: fault detection, fault isolation, fault diagnosis and fault response. FIDEX performs each of these tasks using different rule modules. The sequence of tasks performed are discussed in the following sections.

5.1 TASK 1 - FAULT DETECTION

The purpose of fault detection is to detect any misbehavior in the transponder performance. This task is accomplished by a rule module that continually scans, in a data-driven fashion, the sensor frames which maintain information on the current sensor readings. Fault detection is based on a current reading exceeding a tolerance figure centered on a nominal or expected sensor value. Each sensor frame contains slots for these values. Rules ascribe a qualitative description of each sensor's reading as either GOOD or BAD, depending on whether the current reading is within tolerance. A BAD reading indicates a fault and initiates fault isolation to begin.

5.2 TASK 2 - FAULT ISOLATION

The fault isolation task isolates the suspected fault to one of the transponder's subsystems. This is accomplished by another rule module that considers the qualitative description of all of the signal data contain in the sensor frames. These rules locate a sensor reporting a "GOOD" reading followed by one with a "BAD" reading. The subsystem located between these two sensors is then labelled as faulty.

5.2.1 SENSOR VALIDATION

FIDEX was designed with the ability to identify a faulty sensor. This ability permits the system to avoid the search for a non-existing transponder fault. It could also be used for a reconfigurration of sensors, where faulty ones are removed. Sensor validation is based on simple error propagation. A signal producing a "BAD" sensor reading at one point in the transponder, should result in "BAD" readings in sensors measuring signals dependent on the first signal. FIDEX identifies a faulted sensor if a "GOOD" reading instead is found.

5.3 TASK 3 - FAULT DIAGNOSIS

FIDEX maintains a library of diagnostic rule modules. Each module is designed to address problems with each subsystem within the transponder. Following the isolation task, where the suspected faulted subsystem has been identified, FIDEX loads the appropriate rule module and begins to diagnose the subsystem. Each of the rule-sets perform the diagnosis using a backward chaining approach. The goals for the chosen set represent potential faults for the corresponding subsystem. They are placed on an agenda and pursued exhaustively. The order in which these goals are placed on the agenda is based on the history of the fault states which is maintained in a database. This history is used to order the goals on the agenda. This approach permits FIDEX to pursue the most likely problems first.

5.3.1 INEXACT REASONING

Since one of the constraints that FIDEX needed to work under was limited information on the operation of the transponder, it was designed with the capability to perform inexact reasoning. FIDEX uses an inexact reasoning technique based on the certainty theory (Shortliffe 1975), with some small modification. This technique relies upon establishing a measure of belief (MB) or a measure of disbelief (MD) in a rule's conclusion (H). These two factors can be used to incrementally establish an overall belief or confidence factor (CF) value for H supported by multiple rules through the use of the following equations:

$$MB(H)_{new} = MB(H)_{old} + MB(H)_{new}\ (1 - MB(H)_{old}) \tag{1}$$

$$MD(H)_{new} = MD(H)_{old} + MD(H)_{new}\ (1 - MD(H)_{old}) \tag{2}$$

$$CF(H) = \frac{MB(H)_{new} - MD(H)_{new}}{1 - MIN\ \{MB,MD\}} \tag{3}$$

MB and MD are numeric terms that range from 0 to 1. The CF term ranges from -1 (definitely false) to +1 (definitely true). Values between these two limits represent a degree of disbelief (negative values) of belief (positive values). The term $MB(H)_{old}$ ($MD(H)_{old}$) is the measure of belief (measure of disbelief) established in H from the firing of previous rules. When a new rule fires, it establishes either a $MB(H)_{new}$, if the evidence supports H, or a $MD(H)_{new}$, if the evidence rejects H. This new rule firing is also used to incrementally add to the belief or disbelief in H according to the above equations. If the evidence is in support (rejection) of H, then equation 1 (equation 2) is used. Finally, the overall belief in H is established by equation 3. These equations were embedded in the CERTAINTY ANALYSIS root frame of Figure 7 to permit their inheritance by the lower level frames.

Using this approach, FIDEX can use each piece of available evidence obtained either from sensor data or supplied from the user to incrementally add to the belief of disbelief of each fault state of Figure 7. It also permits FIDEX to conclude that an "abstract fault" exists even if it is unable to determine a "specific fault." For example, it might conclude "I believe that there is an amplifier problem in subsystem_3," instead of "Amp_1 in subsystem_3 has a bad output stage." The following rule illustrates how FIDEX can add to MB or MD of either an object level or class level fault state:

```
IF        The_Fault_Has_Symptoms_In_The_Frequency_Response
AND       {|CH1_BER_SENSORS|}.READING Is "BAD"
THEN      The_LO_May_Be_Out_Of_Phase_Lock
AND       Let Internal_LO_Phase_Lock_Fault.MB = 0.7  ———> specific fault
AND       Let |ATTENUATOR_FAULTS|.MD = 0.7           ———> abstract fault
AND       Let |LO_FAULTS|.MB = 0.5                   ———> abstract fault
```

Given only one piece of evidence, this rule can establish a belief of disbelief in both specific or class level faults. The firing of this rule would also cause an incremental update in the belief of these fault states following the above equations.

5.4 TASK 4 - FAULT RESPONSE

At present, FIDEX performs fault response by providing recommendations on component or sensor reconfigurration. Future plans are to include the capability to reconsider fault diagnosis in the event the recommended action was ineffective. The system will retain its past diagnosis, including recommendations, and reconsider the problem with information made available following the reconfigurration of the transponder.

6. SUMMARY

FIDEX is an expert system designed to perform fault diagnostics on a new satellite developed by NASA Lewis Research Center. It was built with maximum flexibility, both in terms of its knowledge representation architecture and problem-solving approach, in order to adapt easily to changes to the satellite design. It was also designed in a fashion that its performance would naturally improve as performance information became available. The resultant design should be applicable to the diagnostics of other spacecraft systems, where design and performance issues are evolving factors.

REFERENCES

Shortliffe, Edward H. and Bruce G. Buchanan, "A Model of Inexact Reasoning in Medicine," Mathematical Biosciences, Vol.23, 1975.